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Experimental validation of SDHW systems and parametric study on their performance based on dwelling characteristics

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Abstract

This study belongs to a wider project that aims to assess solar irradiance potential at urban scale. Particularly, the annual efficiency of solar energy technologies along with its sensitivity to dwelling characteristics are required. It presents TRNSYS models for two solar water heating systems with either a flat plate or a photovoltaic-thermal collector, which were validated through data collected from daily tests carried out on a test bench. Later, a parametric study is run from annual simulations to correlate their efficiencies and solar output with parameters such as collecting area, roof orientation and number of inhabitants. In the validation, it is obtained a mean error in the daily collector efficiency smaller than 2%, on the heat delivered in the heat exchanger equal to 8.6% and in the thermal efficiency of both systems smaller than 4%. For the annual simulation base case, the flat plate collector system efficiency is 45%, while the electrical and thermal efficiencies of the photovoltaic-thermal system reaches 8.3% and 31%, respectively. The annual efficiency of the systems is mainly sensitive to the number of inhabitants and collectors, varying about a 6% and 3% for each parameter in the photovoltaic-thermal system and about a 7% for both in the flat plate collector system.

Keywords - SDHW Systems, Validation, Simulation, Dwelling

1. Introduction

In the last years, the use of solar energy in dwellings has been encouraged by many governments through public policies that are subject, generally, to the system energy output. Therefore, it is necessary to correctly asses the system efficiency, which varies broadly depending on the individual component performance in addition to system external variables like specific storage volume, total energy demand and total solar energy available as well as their temporal distribution.

Although measurements are the most accurate way to determine the efficiency and solar output, it can be a resource consuming process. Oppositely, simulation models allow to predict the systems performance in less time than experimental testing and under diverse operating and climatic conditions. However, the accuracy of the models must be validated through short-term experimental data.

The objective of this study is to develop a TRNSYS model for indirect and active solar water heating systems based on collector parameters obtained from certification tests under EN-12975 standard, as well as using equipment commonly present in the Chilean market. Even though the TRNSYS models for each system's component are validated, it is attempted to validate the performance of the whole system through experimental measurements taken in a test bench.

Thereafter, the model is used to study the sensitivity of the annual system efficiency by means of a parametric analysis to evaluate which dwelling or systems characteristics influence the systems performance the most. Since then, those parameters can be included into the solar map of the city of Concepción, Chile. This map was previously developed in the context of this research project.

This leads to the following three sections of the present study: test bench experimental characterization, systems modelling and annual simulation.

2. Experimental Setup

Two solar water heating systems with different collectors are analyzed in this study, the first system has a flat plate (FPC) collector and the second one has a photovoltaic-thermal hybrid (PV-T) solar collector. These systems were installed in a test bench located at the *Aerospace Techniques Laboratory* at the *University of Concepción*, Chile.

Both are indirect circuit systems with forced circulation, each one consist of a collector, a storage tank with a mantle heat exchanger, a circulating pump with its controller and piping between all the system's components. The primary circuit, using a mixture propylene-glycol/water (25/75 by volume) carries heat from the collector to the storage tank, while through the secondary circuit circulates the domestic hot water (DHW). All these components are identical in both systems with the exception of the collector and the primary circuit length. The collectors and the indoor components of the test bench are shown in Fig. 1.

Fig. 1. Left: PV-T (upper left) and flat plate (right) collectors evaluated at the test bench. Right: Indoor experimental rig.

It is used a FP and a PV-T collector with an absorber area of 2.23 m^2 and 1.4 m^2, respectively, and orientated towards equator with a tilt of 37°, equal to Concepción's latitude. Further details are summarized on Table 1 [1], [2].

Table 1. Main specifications of tested collectors.

	Flat Plate	**Hybrid**	**Unit**
Rated flow rate	54	45	[L m^{-2} h^{-1}]
Absorber area	2.23	1.40	[m^2]
Optical efficiency	0.795	0.493	[-]
1st order thermal loss coefficient	3.722	4.086	[W m^{-2} K^{-1}]
2nd order thermal loss coefficient	0.012	0.068	[W m^{-2} K^{-2}]
Thermal capacity	9.435	14.3	[kJ m^{-2} K^{-1}]
Incidence angle modifier	0.95	0.89	[-]
Photovoltaic cells area	-	1.125	[m^2]
Module STC electrical efficiency	-	0.109	[-]
PV temperature coefficient	-	0.6771	[W K^{-1}]

Each system has a 160 L vertical tank, where the DHW is heated up through a mantle heat exchanger. ¾" insulated pipes with lengths of 31.9 m for the FPC and 25.2 m for the PV-T system compose the primary circuit.

Energy flows are determined from measurements of ambient temperature, inlet and outlet temperatures at the collector and storage tank, irradiance as well as the primary (water-glycol mixture) and secondary (DHW) flow rates. For the PV-T system, the PV cells are not connected to an electric load, thus only its thermal performance is evaluated. A schematic diagram for both systems is shown in Fig. 2.

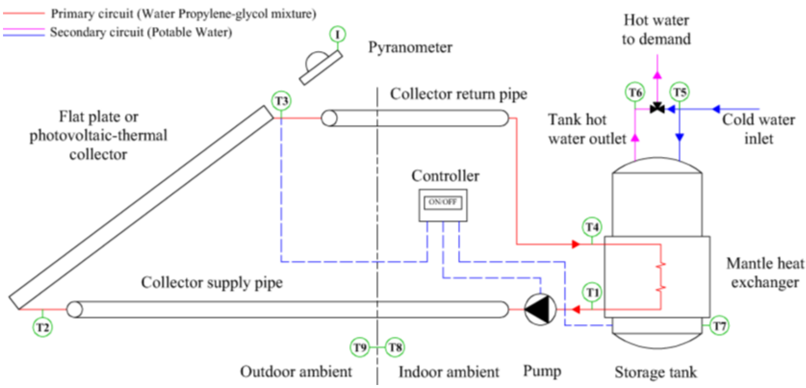

Fig. 2. Schematic diagram of the solar water heating systems in the test bench.

The test bench is equipped with Type T thermocouples to measure temperatures, a second class pyranometer to measure the solar global irradiance at collector's plane and, finally, the secondary flow rate during the draw off is measured by weight.

3. Simulation Model and Experimental Validation

The systems installed in the test bench were modelled using TRNSYS. This software is based on algorithms, called proformas, which represent several kinds of thermal or electrical components. The entire system's model can be constructed by connecting the inputs and outputs of different proformas as they are related in a real system. In this study proformas from the main TRNSYS library and from the TESS library are used.

The following components were used: Type1289 thermal collector, Type604a pipes, Type2 differential controller, Type3d pump, Type109 weather data input (which is replaced by Type9 to read experimental data in the validation step) and Type1237 storage tank. Although the last proforma models a tank with a wrap-around heat exchanger, its parameters are chosen in a way so the convection coefficient inside the mantle is constant and equal to 250 [W m^{-2} K^{-1}], while inside the tank it is calculated by free convection correlations. Fig. 3 shows a flow diagram of the TRNSYS model.

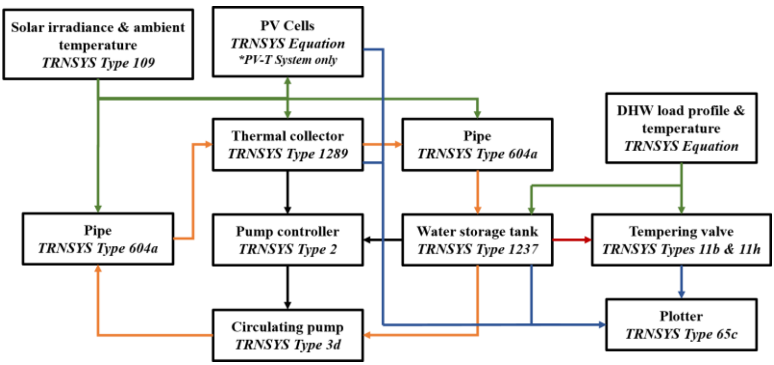

Fig. 3. TRNSYS model flow diagram for both systems.

The experimental validation is divided into three steps: the first and second ones are the collector and the storage tank validation, where the primary flow rate is manually imposed to assess the performance of each component by itself. In the third step the entire model is assembled to evaluate the performance of the solar controller, which defines the working schedule of the pump, and hence the system behavior.

Daily test are carried out at the test bench between May and August 2015 with diverse weather conditions, ranging from covered to sunny days. Seven days are used to validate the collector, five for the tank and two for the whole system. Temperature and irradiance data are acquired every one and five minutes, respectively. Direct and diffuse irradiances are determined from the global irradiance measurements using the Hay-Davies [1] sky model and the reduced Reindl [2] correlation with TRNSYS Types 546 and 16a.

During the test, both systems operate under normal conditions and without DHW consumption. The next morning, before the pump starts, one draw off per system is made to calculate the energy delivered from the system and to define the initial water temperature inside the tank for the next test. The volume of removed water is approximately 2.5 times the volume of the tank to remove all the stored energy.

Fig. 4 shows the flow diagram of components, inputs and output used in TRNSYS to validate the collector and pipes models. The simulated outputs are then compared with the measured ones. The averaged main results of the validation for the collectors are shown in Table 2. The model overestimate the collector efficiency for less than a 2.0% in both systems. Fig. 5 shows an example of the simulated and measured mantle inlet temperature.

Table 2. Collector validation results: Mantle inlet temperature error ($\bar{e}_{T4}$), collector efficiencies ($\eta_{col;exp}$, $\eta_{col;mod}$) and its difference ($\Delta\eta$).

Collector	$\bar{e}_{T4}$ [°C]	$\eta_{col;exp}$ [%]	$\eta_{col;mod}$ [%]	$\Delta\eta$ [%]
FPC	2.3	51.6	53.7	+2.0
PV-T	1.8	27.3	28.8	+1.6

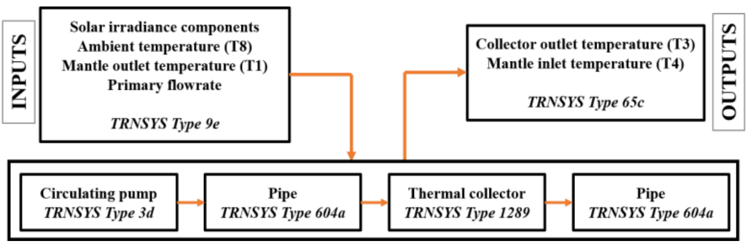

Fig. 4. Flow diagram for collector and pipes models validation.

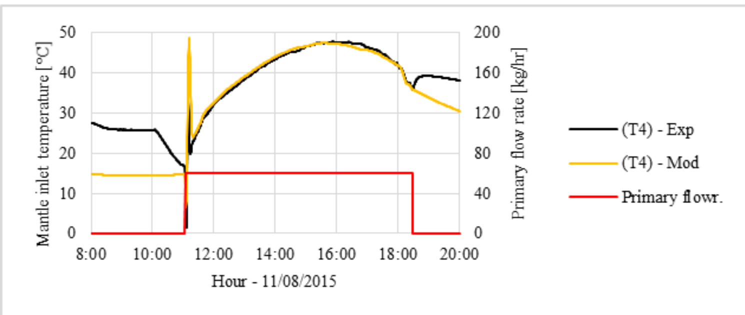

Fig. 5. Measured and modelled inlet mantle temperature for the FP collector validation.

Fig. 6 shows the flow diagram for the tank validation: the outputs are the mantle and DHW outlet temperatures, the mean absolute error of their predicted values is 2.6 [°C] and 1.7 [°C], respectively. This leads to an underestimation in the heat delivered by the solar fluid in the mantle of 8.6% and in the heat provided during the draw off of 6.8%. These errors can be attributed mainly to the constant convection coefficient used in the mantle-side of the heat exchanger.

Fig. 7 shows the thermal power delivered by the DHW as well as the accumulated energy. There is a good agreement between their predicted and experimental values until the draw off ratio (draw off volume over tank volume) reaches 1.3. Since then, there is a difference that can be attributed to mixing inside the tank, which is not considered by one-dimensional tank models like Type1237.

Fig. 6. Flow diagram for the storage tank model validation.

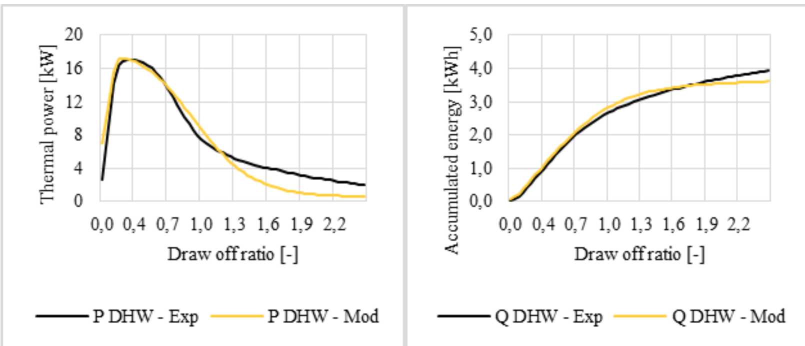

Fig. 7. Modelled and experimental thermal power and accumulated energy in the draw off.

Next, the whole systems are validated to assess the difference between the predicted and experimental pumping period. Fig. 8 shows the flow diagram for this validation step: as inputs are entered external variables like irradiance, DHW flowrate as well as mains and ambient temperatures, while the DHW temperature and the primary flowrate are outputs. Table 3 shows the results of this validation: from the previous steps, the difference in the system efficiency is mainly associated to the tank model. The error on the pumping period is attributed to a deficient placement of the controller sensors located at the collector outlet. Fig. 9 shows the predicted and experimental inlet and outlet mantle temperatures as well as the primary flowrate during a validation test for the FPC system.

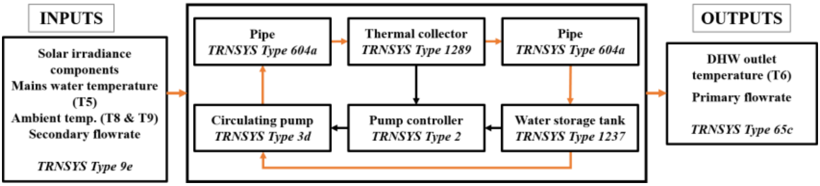

Fig. 8. Flow diagram for the entire system model validation.

Table 3. System validation results: Difference between predicted and experimental system efficiency ($\Delta\eta_{system}$) and pumping period ($\Delta\tau_{pump;on}$).

System	$\Delta\eta_{system}$ [%]	$\Delta\tau_{pump;on}$ [%]
FPC	+1.2	-4.3 (19 minutes)
PV-T	-3.5	+7.9 (32 minutes)

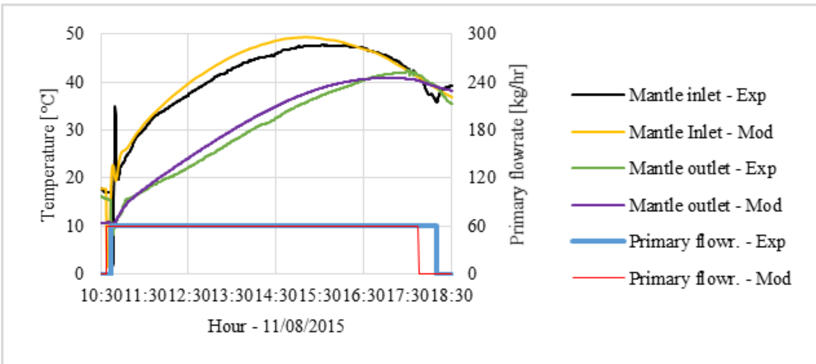

Fig. 9. Simulated and measured mantle inlet and outlet temperature and pumping period.

In all validation steps, the discrepancies in the results can be reduced by improving the instruments accuracy and tests procedures by, e.g., measuring irradiance components separately and reducing water mixing in the tank.

4. Parametric Study on Annual Performance

With the validated models, a parametric study is run based on annual simulations for each systems to evaluate the sensitivity of the solar output to four parameters shown in Table 4. As a base case it is defined a three inhabitants dwelling located in Concepción. The solar energy output is given by (1), where η_{syst}, A_{coll} and I are the system efficiency, collecting area and incident irradiance, respectively.

$$Q_{solar} = I * A_{coll} * \eta_{syst} \quad (1)$$

Table 4. Base, lower and upper parameter values analysed.

Parameter	Base case	Min. Value	Max. Value
Inhabitants number	3	3	6
Collectors number	1	1	2
Roof azimuth	North	East	West
Roof tilt	37 [°]	0 [°]	45 [°]

The results show that these parameters essentially only modify one multiplying factor of (1), and can be grouped as follows: The roof tilt and azimuth change the incident irradiance, while the number of inhabitants and collectors vary the system efficiency in opposite ways. Fig. 10 shows the relative global irradiance on a surface in Concepción depending on its tilt and azimuth. The irradiance is given mostly by the azimuth value, and this is more pronounced to equator-facing azimuths. Indeed, in this case, varying the surface tilt from 27° (best value) to 0° (horizontal) means only an 8% reduction on the annual irradiance.

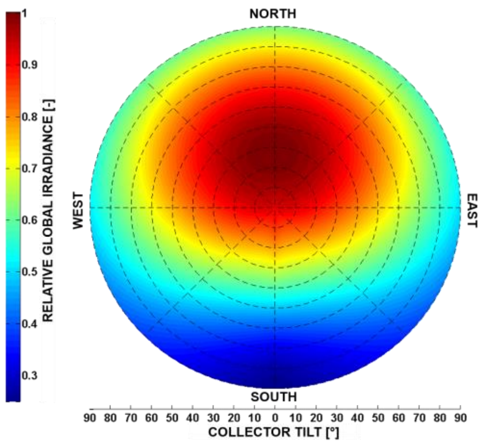

Fig. 10. Relative global irradiance on a surface depending on its tilt and azimuth.

Fig. 11 shows the influence of the number of inhabitants and collectors (hence the collecting area) on the thermal efficiency of both systems. Doubling the collecting area decreases the efficiency almost independently of the inhabitants' number, this drop reaches roughly 7.0% for the FPC and 3.5% for the PV-T system. Oppositely, doubling the DHW consumption (by doubling the number of inhabitants) increases the efficiency following a parabolic curve independently of the collectors' number, this is shown by the first and second order terms of the fitting curves for each system.

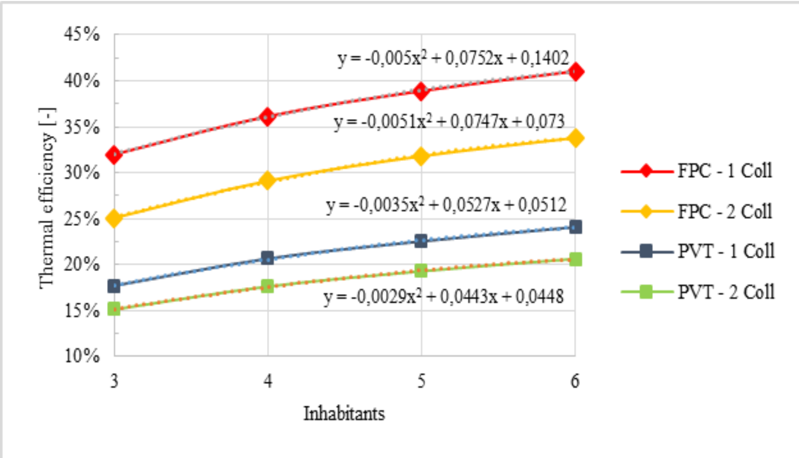

Fig. 11. Thermal system efficiency depending on the number of inhabitants and collectors.

5. Conclusions

Two solar water heating systems with flat plate and photovoltaic-thermal collectors were modelled using TRNSYS. These systems were installed on a test bench to validate the models. First, the collector and the storage tank are validated separately, thereafter, the system is validated as a whole to evaluate the differential controller behaviour.

The validation results are satisfactory, the average difference between the predicted and experimental collector efficiency is less than 2.0% for both systems, the error in the heat transferred from the primary circuit to the DHW through the mantle is 8.6% and in the overall efficiency is less than 4.0%. The main improvements can be made in the instruments accuracy, the test procedures and in the storage tank model.

These results show that it is possible to model accurately the transient performance of the collector, even in cloudy days, from parameters obtained in certification tests using quasi-dynamic models. Besides, a unidimensional storage tank model with a constant heat transfer coefficient on the mantle-side and a variable free convection coefficient on the tank-side is enough to predict the system's energy output with a difference lower than 10% compared to the experimental one.

The parametric study shows the collecting area and the number of inhabitants must be considered in order to correctly asses the thermal system efficiency, which is slightly affected by roof tilt and azimuth. In the case studied, doubling the number of inhabitants from three to six increases the system efficiency in 7.0% for the FPC system and 6.0% for the PV-T system, while doubling the collecting area decreases it in 7.0% and in 3.5% for each system. These two effects are mostly independent of each other, so they can be treated separately.

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